Simulation of Magnetic Pulse Welding with varying Air Gap in Tubular Jobs using FEM

A THESIS SUBMITTED IN PARTIAL FUL FILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Industrial Design

By

Gauresh Ravindra Khanolkar
(Roll: 213ID1362)

Department of Industrial Design
National Institute of Technology
Rourkela-769 008, Orissa, India
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CERTIFICATE

This is to certify that the work in the thesis entitled, "**Simulation of Magnetic Pulse Welding with varying Air Gap in Tubular Jobs using FEM"** submitted by **Mr. Gauresh Ravindra Khanolkar** in partial fulfilment of the requirements for the award of **Master of Technology Degree** in the Department of Industrial Design, National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the work reported in this thesis is original and has not been submitted to any other Institution or University for the award of any degree or diploma.

He bears a good moral character to the best of my knowledge and belief.

Place: NIT Rourkela
Date:

Prof. (Dr.) Mohammed Rajik Khan
Assistant Professor
Department of Industrial Design
National Institute of Technology, Rourkela

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For each and every new activity in the world, the human being needs to learn or observe from somewhere else. The capacity of learning is the gift of GOD. To increase the capacity of learning and gaining the knowledge is the gift of GURU or Mentor. That is why we chanted in Sanskrit "*Guru Brahma Guru Bishnu Guru Devo Maheswara, Guru Sakshat Param Brahma Tashmey Shree Guruve Namoh*". That means the Guru or Mentor is the path of your destination.

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Gauresh Ravindra Khanolkar

ABSTRACT

Magnetic pulse welding process, one of high speed welding processes, uses electromagnetic force from discharged current through a working coil which develops a repulsive force between the induced currents flowing parallel and in the opposite direction in the work piece to be welded. Coils of specific geometry and material combinations are essentially required to achieve precise and successful electromagnetic (EM) welding. The aim of the present research is to assess the weldability criteria of high speed magnetic pulse welding for tubular jobs of Al, Cu and SS combinations using finite element analysis. A circular design of EMW coil is proposed to perform EMW simulations while varying the air gap between the outer tube and inner tube of different work pieces and voltages. A 3-dimensional electromagnetic FE-model has been developed to analyze the distribution of electromagnetic force and magnetic flux density. Results of electromagnetic forces and magnetic flux density acquired during EMW simulations of various material combinations are shown here. The data shown in the results provides a guideline to choose EM welding parameters for further experimentations. The demonstrated results will assist future researchers to develop a better methodology for coil design and to further explore the field.

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ACRONYMS

1. EMW – Electromagnetic Welding
2. MPW – Magnetic Pulse Welding
3. Al – Aluminium
4. SS – Stainless Steel
5. Cu – Copper

CHAPTER 1

1. Introduction

1.1 Background

Welding is a joining process in which two materials; usually metals are joined together by sufficient penetration of the metals into each other by melting them at a higher-melting-point. Generally, a filler material is added at the interface to form a bond between the materials to be welded. At times, the bonding is also achieved without the use of filler material. The melting of the materials forms a molten pool of metal also known as the weld pool. This results in a welded joint when the metal finally solidifies causing coalescence. Sometimes pressure is applied along with heat to produce the weld. Atomic bond is established in all the welding processes.

Welding is usually classified into:-

a) Solid state welding
b) Liquid state welding
c) Solid/Liquid state welding

1.1.1 Solid state welding

Solid state welding is an amalgamation process in which pressure, time and temperature, individually or in combination, without melting the work pieces, produce coalescence of the work pieces. It is also called as a cold welding process. Therefore, there are no thermal changes in the properties of the work pieces. This type of welding is preferred, where the metal characteristics must remain unchanged after welding. Solid state welding requires the surfaces to be clean. Solid state welding includes the processes like diffusion welding, friction stir welding, electromagnetic welding etc. The metals retain their original properties since there's no melting of the base metals. These processes are ideally suited for joining dissimilar metals with wide difference in their melting points.

i. **Shielded Metal Arc Welding**

Shielded Metal Arc Welding or "SMAW" is the most commonly used welding process. The power supply is turned on, and the user is made to strike the metal to ignite it which forms the arc and the electrode begins to burn. This creates a shielding gas and deposits metal into the joint that is being welded. The slag from the electrode needs to be cleaned or chipped off as soon as the weld is finished.

ii. **TIG Welding**

Gas Tungsten Arc Welding or "GTAW", as it is commonly called, is an arc welding process that uses non-consumable tungsten electrode. A shielding gas viz. argon or helium is used to shield the welding area from atmospheric contamination. Invariably, a filler material is used. A constant-current welding power supply is used and it produces energy, which is conducted across the arc through a column of highly ionized gas and metal vapors known as a plasma. TIG welding is mostly used when welding of different metals is to be achieved. Welding done by TIG process produces the highest quality weld! TIG welding is mostly used for complex jobs where there's a presence of critical weld joint.

GTAW is most commonly used to weld thin sections of stainless steel and non-ferrous metals such as aluminum, magnesium, and copper alloys. The process grants the operator greater control over the weld than competing processes such as shielded metal arc welding and gas metal arc welding, allowing for stronger, higher quality welds. However, GTAW is comparatively more complex and difficult to master, and furthermore, it is significantly slower than most other welding techniques.

iii. **MIG Welding**

Gas metal arc welding (GMAW), which is also commonly known by other names like, metal inert gas (MIG) welding or metal active gas (MAG) welding, is an arc welding process that uses a consumable wire electrode to weld the metallic job-pieces. The electric arc formed during the process heats the job-pieces causing them to melt and form a molten weld pool, which later solidifies to form a welded joint. A shielding gas is used – which shields the process from outside contamination – and it is fed through the welding gun along with the wire electrode. A constant voltage, direct current power source is most commonly used with GMAW, but constant current systems, as well as alternating current, can be used. GMAW is the most common industrial welding process, preferred for its versatility, speed and the relative ease of adapting the process to robotic automation.

iv. Ultrasonic Welding

It is a solid state welding process. In this process coalescence is produced at the joining surfaces by the application of high frequency vibratory energy. The job pieces are held together under fairly low static pressure. Ultrasonic welding uses the heat generated from high frequency ultrasonic motion to join thermoplastics. This is achieved by converting high frequency electrical energy into high frequency mechanical motion. Frictional heat is created at the mating surfaces because of mechanical motion and applied force of the plastic components. The material melts at the surface and forms a molecular bond between the work pieces to be welded. Around 20 to 40 kHz frequency is generated.

v. Explosive Welding

Explosion welding (EXW) is a solid state process. In this process welding is achieved by using chemical energy to accelerate one of the components at a tremendously high velocity. Feasible geometries are very limited due to the nature of this process. They must be simple. Plates, tubes and tube-sheets are some of the common geometries produced.

vi. Friction Welding

Mechanical friction generates heat between a moving work piece and a stationary component with the addition of lateral force to plastically displace and merge the materials together. This results in a welded joint. It is a solid state welding process. Technically, friction welding is more of a forging process than a welding process – as melting of the work piece doesn’t occur. Friction welding has varied applications in aviation and automotive industries. In friction welding, the heat is produced by the friction between the work pieces to be joined. Work pieces are held under pressure during the process; one part is stationary and other part is made to rotate at high speed. The welded joints is obtained when a force on the stationary part is applied after stopping the rotation of the part to get the welded joint.

1.1.2 Liquid state welding

In this process, the work pieces in and around the area to be welded are melted. The fusion takes place because of heat, and sometimes pressure. It may involve the use of filler materials such as consumable electrode or a wire fed into the weld pool. The process is either autogenous or heterogeneous. Depending on the application and requirement, different type of fusion welding processes are chosen. Eg. Electric arc welding, induction welding etc.

1.1.3 Solid/liquid state welding

The processes such as brazing, soldering and adhesive bonding are classified as solid/liquid state welding. In these processes the base material is not melted. A molten filler material is used for welding the joint.

1.2 Problems in Traditional Welding Processes

In traditional welding techniques, the welding is achieved by melting the work pieces and adding a filler material to form a pool of molten metal which then solidifies to form a welded joint. This welded joint is often left with tool marks on its surface. The tools marks viz. scars, burrs etc. are a result of mechanical contact between the job pieces during the process. In Electromagnetic welding, there's no mechanical contact between the work pieces of any kind i.e. the welding is achieved by non-contact method. Therefore, the mechanical faults like scars, burrs etc. are eliminated and a smooth surface finish is obtained. Also, in traditional welding processes, there's a need for surface preparation of the jobs, preheating etc. Such prerequisites are not needed in Electromagnetic welding.

Joining of dissimilar metal combinations is a challenging task, since it's difficult to weld dissimilar material combinations due to difference in their melting points. Electromagnetic welding is a solid state welding process. Thus, it does not involve melting of work pieces, and thus is a good alternative for welding these materials.

It's difficult to weld Aluminium, given its high affinity for oxygen. The oxidation of Aluminium is a major concern during welding as the oxide layer gets trapped in the weld zone. Also, Aluminium is preferred in automobile industries as it is a light weighted material.

Reduction of weight leads to efficient fuel usage; hence use of lightweight materials is vital in automobile industry. The use of aluminium and its alloys is going to increase in future (especially in automobile and aerospace industries). But Aluminium is not so strong mechanically, which makes welding of Aluminium a difficult proposition. Therefore, a trade off can be reached and Aluminium can be welded with other mechanically strong materials. Many industrial applications require welding of dissimilar metals such as Copper, Aluminium, and Stainless Steel in many engineering applications. Electromagnetic welding is the answer to these problems.

Copper has high thermal conductivity. Therefore, before it reaches the melting temperature, most of the heat is dissipated. Also, welding Stainless Steel to Copper is a difficult prospect as the solubility of Fe in Copper is very less. Electromagnetic welding addresses this problem as it is a solid state welding process i.e. no melting of the work piece occurs.

1.3 Principle of operation of EMW

Magnetic pulse welding also known as electromagnetic welding is a solid state welding process in which the materials to be welded are impacted against each other at high speed with the help of electromagnetic forces (Fig. 1.1 to 1.3). Electromagnetic welding differs from the traditional welding processes in a way such that, EMW is a solid state welding process, thus, the welding occurs at room temperature. Electromagnetic force is used to weld the materials by impacting them against each other at high velocities i.e. the welding is obtained by impact force. The coil is made up of a high conducting material. The welding is done without any physical contact with the work-piece, therefore there are no defects viz. burrs or scars on the surfaces of the welded jobs. The working coil design is a vital factor. It's the most important factor since the working coil has to generate a high-intensity magnetic field. The capacitor bank is charged using a power supply. When the necessary quantity of energy is stored in the capacitor bank, it is released into the coil. A strong transient magnetic field is induced by the discharge current into the coil. This in turn induces eddy currents in the outer work piece, which is situated within the working coil which then generates the Electromagnetic force as per Fleming's left-hand rule (Fig. 1.3).

The outer work piece impinges upon the inner work piece at high velocity thereby resulting in an impact bond. The job pieces become semi-viscous and penetrate into one another. The work pieces do not melt hence, no fusion occurs. Therefore, no thermal changes are observed in the material properties in this process. Due to this property of Electromagnetic welding, dissimilar materials with erratic melting points can be joined together. This is not possible with traditional welding techniques.

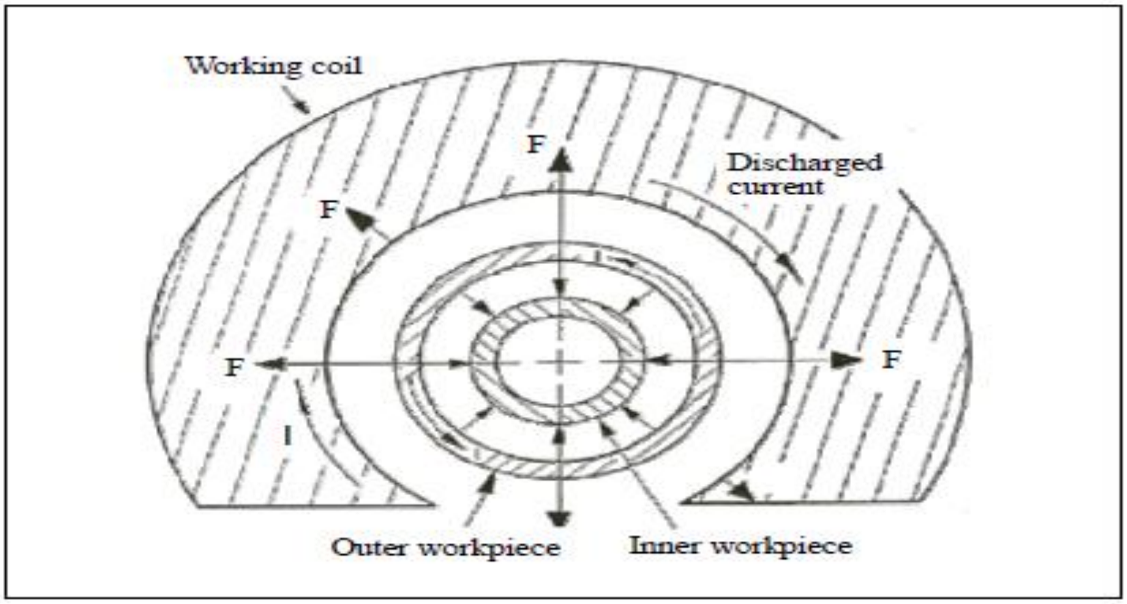

Fig 1.1 Principle of Electromagnetic welding [14]

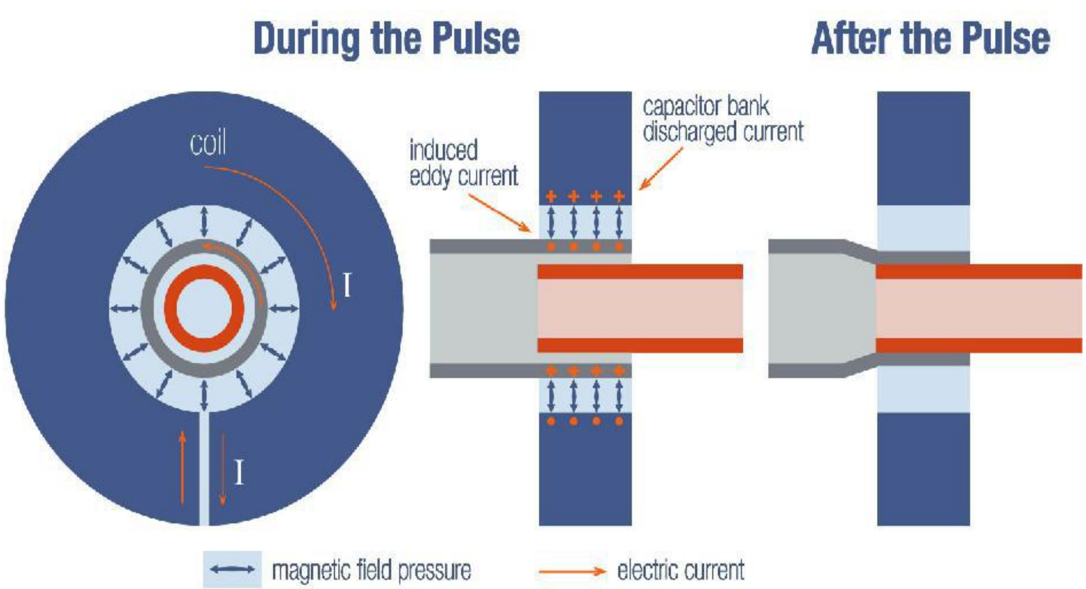

Fig 1.2 Schematic diagram of Electromagnetic welding operation [25]

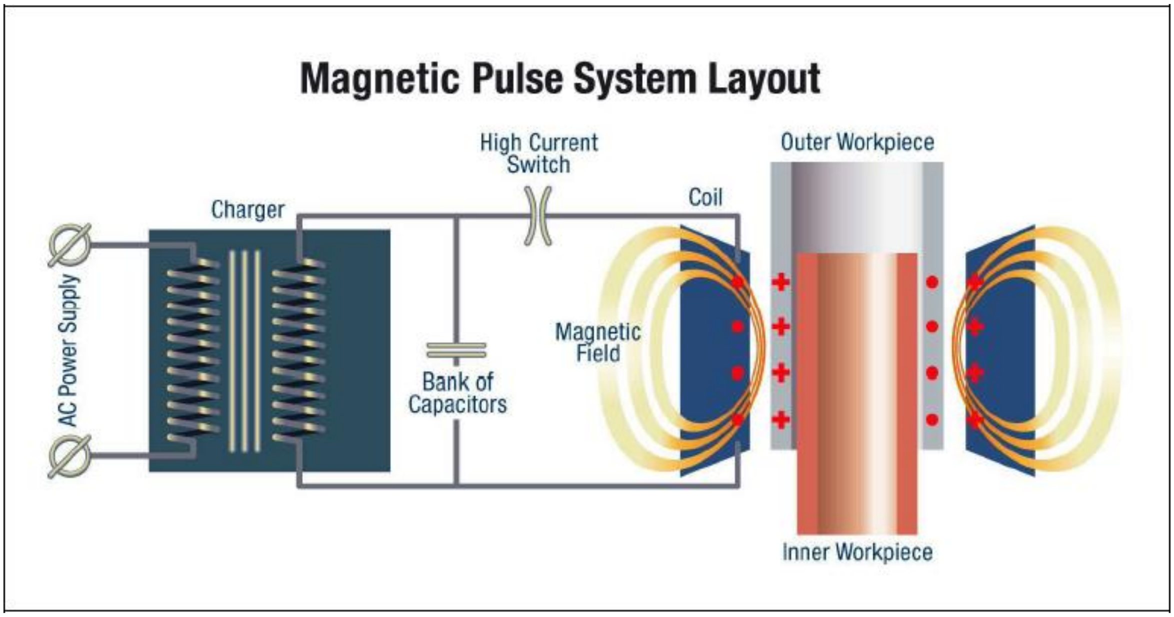

Fig 1.3 Schematic Diagram of Electromagnetic Welding process [24]

In electromagnetic welding, the work-piece is placed in close proximity to the EMW coil and has good magnetic coupling with the latter. This which causes the discharged current to pass through the working coil. The product of magnetic field and discharged current gives rise to the electromagnetic force (Lorentz force) between the induced currents in the work piece to be welded, which is repulsive in nature i.e. it is directed away from the coil. According to the principle of mutual inductance of transformer, the welding coil behaves like a primary winding of the air core transformer, and the work piece behaves as a short circuited secondary which causes the conductors carrying currents (in opposite direction) to repel each other as induced currents in the job piece are predominantly in anti-phase with the coil current; the induced current and coil current vary sinusoidally. There exists a repulsive force between the coil and work-piece.

The work piece, high voltage charging supply, welding coil, capacitor bank spark gap switch etc. are the main components of Electromagnetic Welding process. The capacitor bank is initially charged to a high voltage. This energy is then discharged into welding coil. In the positive half cycle, the energy is delivered from the capacitor to the inductor, and in the negative half cycle, the inductor returns the energy back to capacitor. However, the current decreases continuously due to dissipation in the resistance of the circuit. The under damped circuit current waveform looks like as shown in the Fig. 1.4.

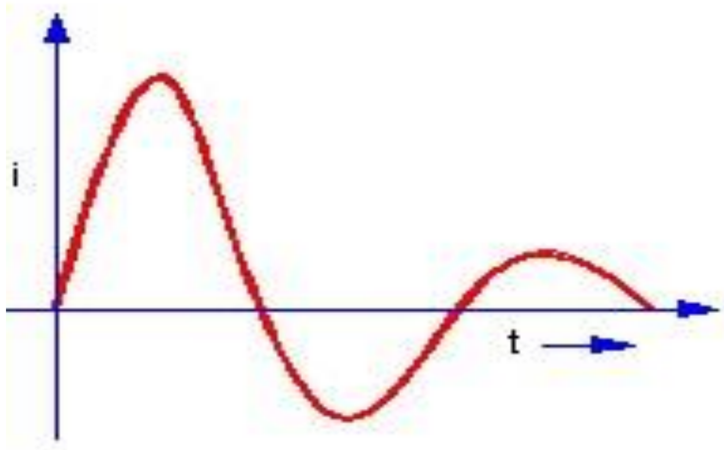

Figure 1.4. Current waveform in an under damped circuit [22]

1.4 Salient features of Electromagnetic Welding

EMF technique has the following salient advantages –

1. In electromagnetic welding process, the welding takes place by electromagnetic force. Therefore, there is no physical contact between the coil and the work piece. Therefore there are no tool marks on the job piece.
2. It's a high speed operation. The job-pieces are welded in a few microseconds.
3. Repeatability is very good since it is governed by fixed electrical parameters.
4. Since there's no manual operation involved, the process can be easily automated and also it reduces the number of manual errors involved.
5. The process can be easily automated which can result in high production rates.
6. No need of surface preparation, preheating the surface etc. EMW eliminates the need of preparatory methods.
7. In EMW process, the work pieces are plastically loaded at a very fast rate, thus, it eliminates any spring back effects.
8. No need to create a vacuum environment for welding operation.

1.5 Advantages

1. EMW has an advantage over Electromagnetic explosive welding technique, which is similar but has disadvantages like safety and space requirement.
2. Materials with widespread and erratic melting points can be easily welded by EMW. Since, welding is done by impact bonding and not melting of the work pieces. Also, thermal property changes in the material, if any, are eliminated. The problems of stress relieving due to heat are eliminated.
3. The investment cost for EMW equipment is relatively less when compared with Electron Beam welding for related applications.
4. The welding of high refractory materials such as Tantalum, Titanium, Niobium etc. can be easily done with EMW process, which otherwise posed a challenge with traditional welding processes.

1.6 Disadvantages

1. Non – conductive materials can't be welded using Electromagnetic welding process. Since the efficiency of the EMW depends on the electrical conductivity of the job material, it is more suitable for good electrical conductivity metals. This drawback can be partially overcome by using conducting drivers.
2. Skin depth is less. Thus, it's only suitable for jobs having small thickness.
3. EMW is not suitable for large size jobs (exceeding 1metre). With the increase in the size of the circuit, the circuit inductance increases. Due to large value of inductance, the ringing frequency gets lowered. At lower frequency, more magnetic field gets diffused out of the job, which eventually lowers the Lorentz force.

1.7 Applications of Electromagnetic Welding

The Electromagnetic Welding is in its infancy as far as its commercial application is concerned. There has been research done in plate to plate and sheet to sheet welding, but very less research has been done in welding of tubular job pieces. After taking into consideration the advantages and limitations of the Electromagnetic welding process, one can come to the conclusion that, many aspects in tubular welding jobs could be explored for different engineering machine part applications. Few of the applications are, welding of a tubular collar on a rod, sealing of tubular jobs with end plugs. Many potential applications exist for flat geometries in automobile industries and aerospace industries. The weight of the automobile can be reduced by using lightweight materials like Aluminium. But it being light weight, it lacks the desired strength. So it could be welded with strong materials like Stainless steel etc. EMW offers solution to such problems since it's easy to join dissimilar metals. High refractory materials like Tantalum, Niobium, Titanium etc. could be welded since EMW doesn't involve melting of the work pieces.

1.8 Necessity of Present Research Work

There are two major challenges in the current traditional welding processes.1) Welding of Aluminum and 2) Welding of dissimilar material combinations. Aluminium has a very high affinity for oxygen. Aluminium forms aluminium oxide when exposed to atmosphere. Also, Aluminium being light in weight is preferred in automotive industry. Thus welding of aluminum is an issue. Also, welding of dissimilar material combinations is an issue owing to large difference in their melting points. Electromagnetic welding offers solutions to these problems since it's a solid state welding process. Also, the welding is done by impact force rather than melting, and hence it's ideally suited for joining dissimilar material combinations having a high difference in their melting points.

In electromagnetic welding the oxide layer is destroyed by impact force, which eliminates any need for surface preparation. This process of breaking the oxide layer by impact force is called "jetting" process. It's very helpful in welding Aluminium.

Currently, some work has been done on the electromagnetic welding of sheet to sheet jobs or plate to plate work pieces. But very limited, or no work is done in the field of electromagnetic welding of tubular jobs which have applications in nuclear, automotive and aerospace industries.

The Magnetic pulse welding process is presently in very limited use. Hence, there is the need for creation of the data base as regards the equipment and the process. We have carried out the analysis of the system parameters and their dependence on the EMW process. This includes the standoff distance, or air gap, of the tubular work pieces; the capacitance and inductance of the coil; ringing frequency; area of working coil; operating voltage during welding.

Not enough date is available on standardization of input parameters (voltage, capacitance, inductance etc.) for the tubular jobs of different sizes. Widespread data is available for welding combinations of Aluminium, Stainless steel, and Copper for both similar and dissimilar combinations, for different values of input parameters for sheet to sheet jobs but none is available for tubular jobs.

Refractory materials e.g. Titanium, Niobium etc. will increase in future. Refractory materials are thermally very stable at high temperatures. But it is difficult to weld them due to their high melting point. Since Electromagnetic welding is an impact welding process, therefore, there's no melting of the work pieces. Also, EMW requires that the materials be ductile at room temperature, as it's a cold welding process, and refractory materials possess those properties. Thus, Electromagnetic Welding is the suitable process to weld these materials. Welding of tubular jobs of refractory materials like tantalum, ODS steel etc. with Al, SS etc. are currently being researched at BRNS, Mumbai.

1.9 Objectives

- To design an improved cross-section of EMW coil for welding of various combinations of tubular jobs.
- To generate 3D finite element model of coil to analyze the distribution of electromagnetic force and magnetic flux density.
- To determine the air gap between the outer tube and inner tube and input voltages required for successful welding of tubular jobs of Al, Cu and SS combinations.

CHAPTER 2

2. Literature Survey

2.1 Overview

Welding, as existing fusion welding, generally causes not only defects, such as solidification, cracking, porosity and oxidation, but also transformation and corrosion. For this reason, more attention has been paid to magnetic pulse welding process as a kind of solid-state welding, these days. Electromagnetic (EM) welding is an impact welding process of joining two similar or dissimilar metals by removing oxide layer and by creating a high velocity impact by Lorentz forces generated due to the electromagnetic field and damped sinusoidal transient current. It offers many distinct advantages, provided it is used, taking into account its limitations. For successful magnetic pulse welding, it is important to develop a working coil that can gain enough electromagnetic force for welding. The coil design is a complex task and mainly includes the assessment of appropriate coil materials, sizes, the electromagnetic parameters such as capacitance, inductance, resistance and the magnetic field as well as thermal and stress loadings. The extensive knowledge in this complicated area is not easily obtained, as the variety of experimental setups and the complicated dynamic interaction between different phenomena in the welding process are extremely difficult to describe in a closed analytical form. The literature survey has been classified into

a) International research
b) National research

2.1.1 International research

Most of the work is concentrated on the foundation of the theoretical analysis of electromagnetic forming of various materials [1-2]. The EM forming process for flat sheets and axisymmetric components (tubes) has been studied in detail by many researchers [3-4]. Many efforts have also been done in using Al sheets for electromagnetic welding of flat sheets for similar and dissimilar metals [5-6]. The field of EM welding has also been explored for joining similar and dissimilar metal tubes [8–10]. Li et al. [11] have presented a numerical simulation of the magnetic pressure in tubular working coil. Recently, the study on tubular structure of square working coil has been reported by Shim Ji-Yeon et al.

[12] have analyzed the distribution of electromagnetic force of square working coil for magnetic pulse welding. For this, they developed a FEM model which was used to analyze the distribution of electromagnetic force; after that, distribution of electromagnetic force, results of numerical analysis and experimental results for verifying the developed FE-model were compared. Published literature on numerical modeling of EM welding of flat sheets and axisymmetric jobs are scarce. Further detailed study of the effect of process parameters, coil design, etc. on strength of electromagnetic welding of tubular jobs of dissimilar materials has not been reported yet. Kim et al. [13] have investigated the efficiency of the joint designs for EMW of ring- shaft assembly. Aizawa T [7] et al. have demonstrated the Magnetic pulse welding method and its application for several aluminum alloys (A1050, A2017, A3004, A5182, A5052, A6016, and A7075). They've also reported the welding process parameters.

2.1.2 National research

Some work has been done nationally in the direction of EMW of flat sheets of similar/dissimilar material combinations which were difficult to weld using conventional welding techniques. Kore et al. (IIT Guwahati) [14-20] has widely established EMW of Al-to-Al, Al-to-Cu, Al-to-SS, Cu-to-SS, Cu-to-Cu, Mg to Al and Al-to-Al-Li flat sheets. Further detailed study of the effect of process parameters on strength and width of electromagnetic impact weld of Al-to-Al and Al-to-SS have also been reported by Kore et al. [14-15]. Rajawat et al. (BARC Mumbai) [21] have discussed about the salient features of EM forming with potential benefit to accelerator technology. The relationships between capacitor input energy, ringing frequency and the sizes and the materials of the jobs to be welded (in similar and dissimilar combinations) has been given by Desai et al. (BARC Mumbai) [22-23]. Still, major attempts are required in the area of EMW coil design and investigation of microstructure and metallurgical analysis of weldments to access weld quality and performance. Also, no work has been reported nationally for the EMW of tubular jobs with Al/SS/Cu/ODS tubes. Such joints are very much desired to serve at very high temperatures without failures in heat exchangers, nozzles, etc.

CHAPTER 3

3. Development of circular working coil

3.1 Design of Working Coil

There are no given set of rules or guidelines to design the welding coil. Thus, a new approach has been discussed in this project. A single turn welding coil has been considered in this project. Firstly, the geometry of the welding coil is decided, which not only depends on the geometry of the work-piece to be welded, but also on the welding direction, according to the application. Secondly, distribution of electromagnetic force by the interaction between working coil and outer pipe is investigated after selecting materials whose electric resistance is low and those who have enough strength possible to resist electromagnetic force on processing.

The values of process parameters like capacitance were assumed from literature survey and from standard information available. To meet the demands of higher energy and higher ringing frequency, it is advised to use capacitance bank of higher voltage and low capacitance for low conductivity materials. $R = 10\ m\Omega$, $L = 70\ nH$ and $C = 400\ \mu F$ are the process parameters for the given study.

For welding of tubular jobs there are two types of working coils viz. expansion type and compression type. A compression type welding coil is the solenoid type, which houses the work pieces within itself, and the welding takes place from outside direction to inside direction. Expansion coil is placed inside the materials to be welded and welding takes place from inside to outside direction. The compression type coil was chosen in this project to weld tubular jobs because it is located outside of the work pieces. In addition, it has no size limit, as well as it only requires a simple connection to the power source.

The design procedure can be split into following steps:

1) Calculation of ringing frequency and magnetic field
2) Calculation of current required in coil
3) Calculation of Cross Section area of the coil

3.1.1 Calculation of ringing frequency and magnetic field:

The main dimensions of the coil such as length and width are decided based on the dimensions of the job piece. Calculate the ringing frequency and the magnetic field required to be produced by the coil.

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

where,

f – Ringing frequency (Hz)

L – Inductance (H)

C – Capacitance (F)

$$P = \frac{B^2}{2\mu_0} = \frac{\mu_0 H^2}{2} \tag{2}$$

where,

P – Electromagnetic force

B – Magnetic flux density

H – Magnetic field strength

μ_o– Permeability of free space ≈ 4π×10-7 V·s/(A·m) ≈ 1.26×10-6 T-m/A

3.1.2 Calculation of current required in coil:

The separation between coil and job-piece, in principle, should be as minimum as possible, for the best coupling of magnetic flux between coil and job-piece. An insulation of 1mm mm thickness is maintained between the coil leads and the job piece.

$$I(\mathrm{t}) = V_0\sqrt{LC} * e^{-\varepsilon\omega t} * \frac{\sin(\omega t)}{\sqrt{1-\varepsilon^2}} \tag{3}$$

where,

ε = Damping factor (0.3)

w= 2 πf

f = Ringing frequency (Hz)

C = Capacitance (F)

L = Inductance (H)

V_0 = Input voltage

3.1.3 Calculation of Cross Section area of the coil:

$$\mathrm{A} = \mathrm{L} * \frac{\mathrm{l}}{(2\mathrm{N}\mu)} \tag{4}$$

where,

L – Inductance (H)

N – Number of turns (N=1 for single turn coil)

μ - Permeability of core material (T-m/A)

A – Area of coil (m^2)

l - Length of coil (m)

$\mu = \mu_r \mu_o$

μ_r – Relative permeability

μ_o – Permeability of free space ≈ 4π×10-7 V•s/(A•m) ≈ 1.26×10-6 T-m/A

3.2 3D Model generation of EMW Coil

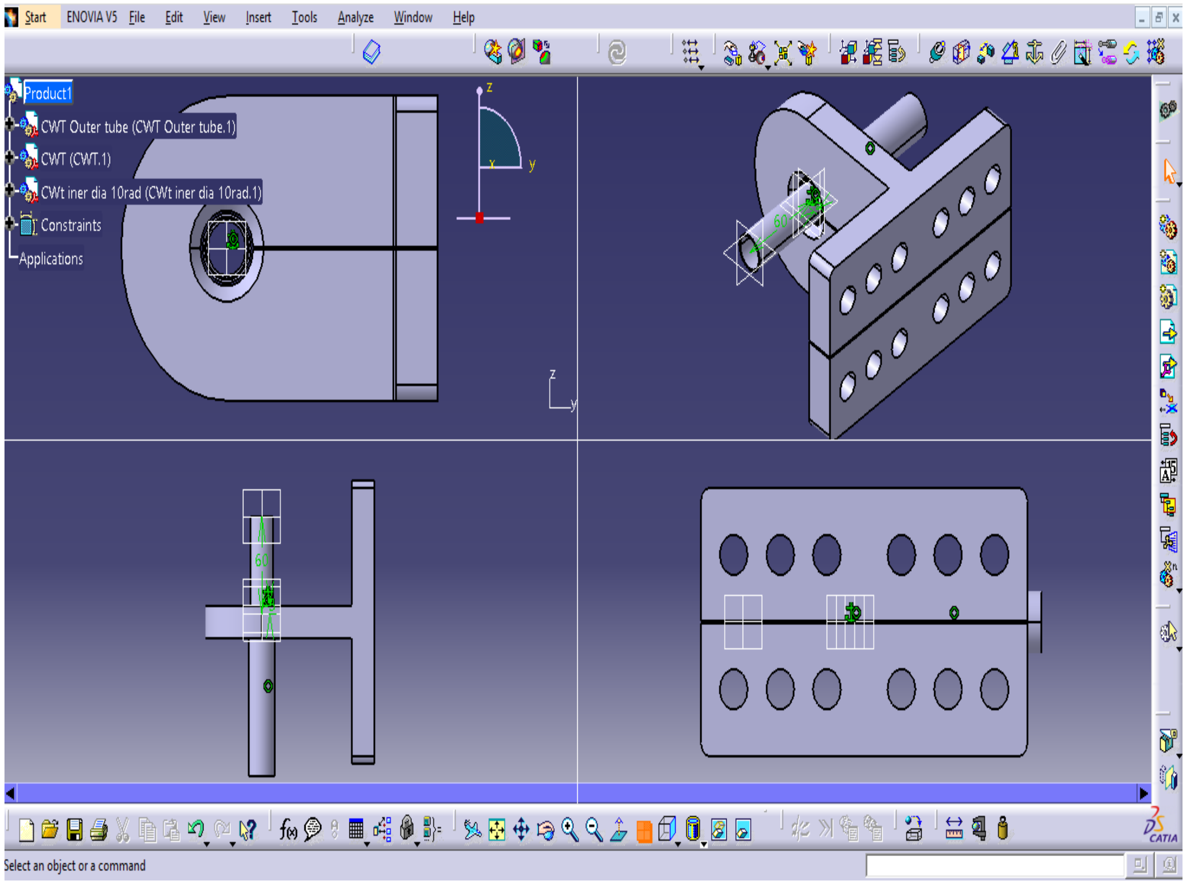

Fig 3.1 3D CAD model of working coil with tubular work pieces

The electromagnetic working coil is the most critical component of the electromagnetic welding process. The material of working coil should be conductive i.e. it should allow the current and magnetic lines of flux to pass through it. Also, it should be mechanically strong to sustain deformation and electromagnetic forces during the welding process. Therefore, Stainless steel and Copper have emerged as the suitable candidates for the working coil material in this project. Also, it can be seen from the figure that the coil is tapered near the inner end towards the work piece. Corresponding to this area is the region where welding takes place. The reason for making it tapered is that, more current will pass through the lesser area, which in turn will result in more magnetic lines of flux passing through it, which in turn will generate more electromagnetic force, thus resulting in a better weld.

The high magnetic field is produced at its inner diameter. The coil has holes at one of its ends to attach it to a fixture. An insulation gap of 1 mm is provided between the ends. Fig 3.1 depicts the CAD model of the circular working coil with tubular work pieces. It is made in a 3D CAD modeling environment viz. CATIA V6. The coil dimensions were decided after using the above based formulations and after studying the literature.

CHAPTER 4

4. Finite Element Simulation of Electro Magnetic Welding

The 3D CAD model of circular coil generated in the previous chapter is then imported in ANSYS Maxwell 3D. ANSYS Maxwell is the electromagnetic field simulation software tasked with designing and analyzing 3-D and 2-D electromagnetic and electromechanical devices, including motors, actuators, transformers, sensors and coils. Maxwell uses the accurate finite element method to solve static, frequency-domain, and time-varying electromagnetic and electric fields. After importing the 3D CAD model into ANSYS Maxwell 3D, we have created a region (environment) where the boundary conditions like insulation sheet, coil terminals, windings, etc. are applied.

After giving the boundary conditions, time varying current, as stated in equation 3, is provided as input to the 3D FE model. Coil materials of SS and Cu have been used for the welding simulation of various material combinations viz. Al-SS, Cu-SS, and SS-SS with varying air-gap from 0.5mm, 1mm and 2mm for each of the combinations. At 12KV the maximum current was generated at 7μs and it was found out to be 0.591MA. At 14KV, the maximum current was generated at 7μs and it was found out to be 0.689MA. And at 18KV, maximum current was again generated at 7μs and it was approx. 0.887MA. Detailed FEM simulation results have been shown below.

4.1 Simulation of EMW of Al-SS work pieces with Cu coil

The following simulation results (Fig. 4.1 to 4.3) are shown for electromagnetic welding of Al-SS tubular work pieces with Cu coil at an air gap of 0.5, 1.0 and 2.0 mm respectively. At an air gap of 0.5mm, for the process parameters of 12KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 19.58T and 26.25T resp. and the maximum electromagnetic force generated is 195.83N. Fig (4.1) shows the results.

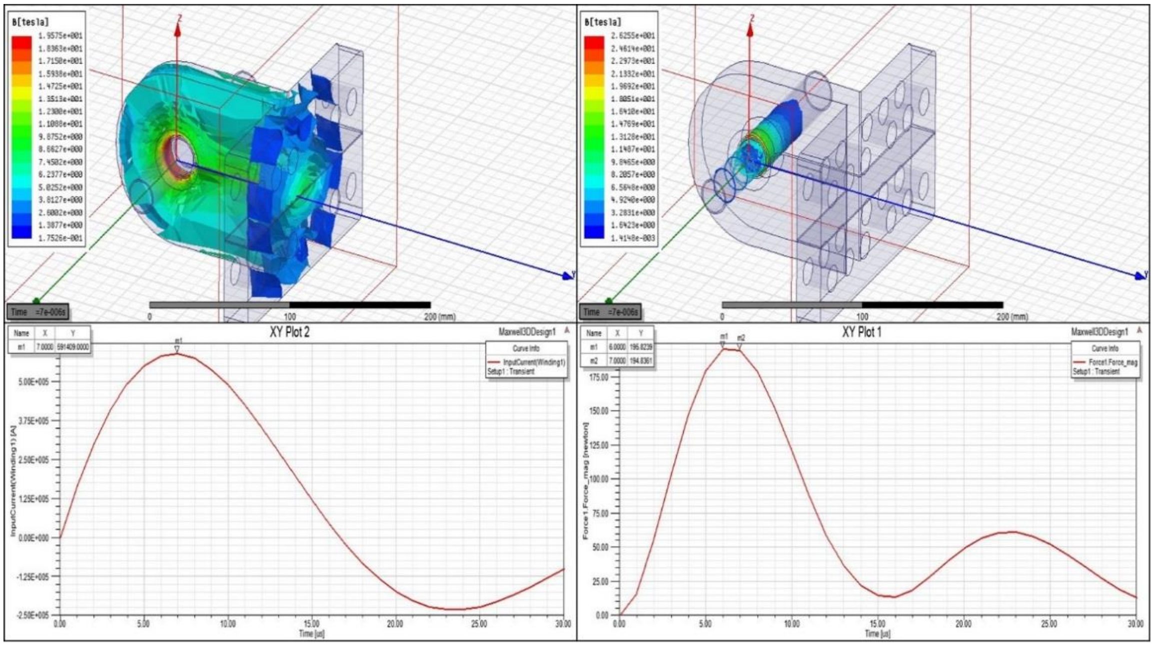

Fig 4.1 Cu Coil, AL – SS work pieces, 0.5mm Air-gap

At an air gap of 1mm, for the process parameters of 12KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 19.82T and 34.23T resp. and the maximum electromagnetic force generated is 360.276N. Fig (4.2) shows the results.

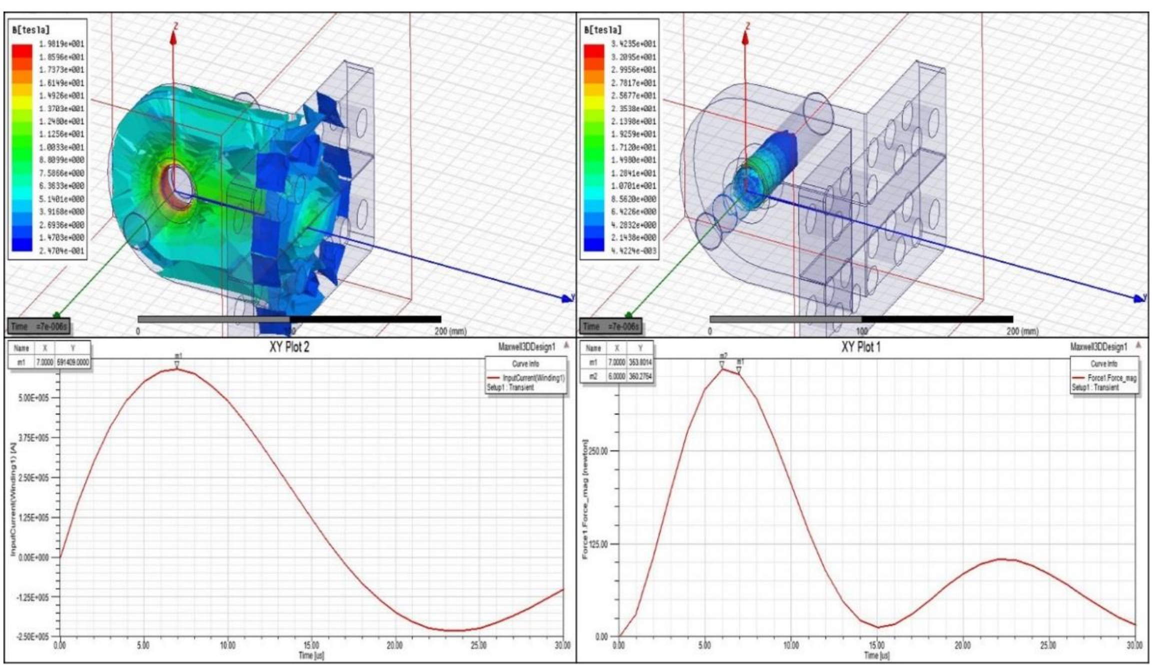

Fig 4.2 Cu Coil, AL – SS work pieces, 1mm Air-gap

At an air gap of 2mm, for the process parameters of 12KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 19.48T and 27.31T resp. and the maximum electromagnetic force generated is 221.97N. Fig (4.3) shows the results.

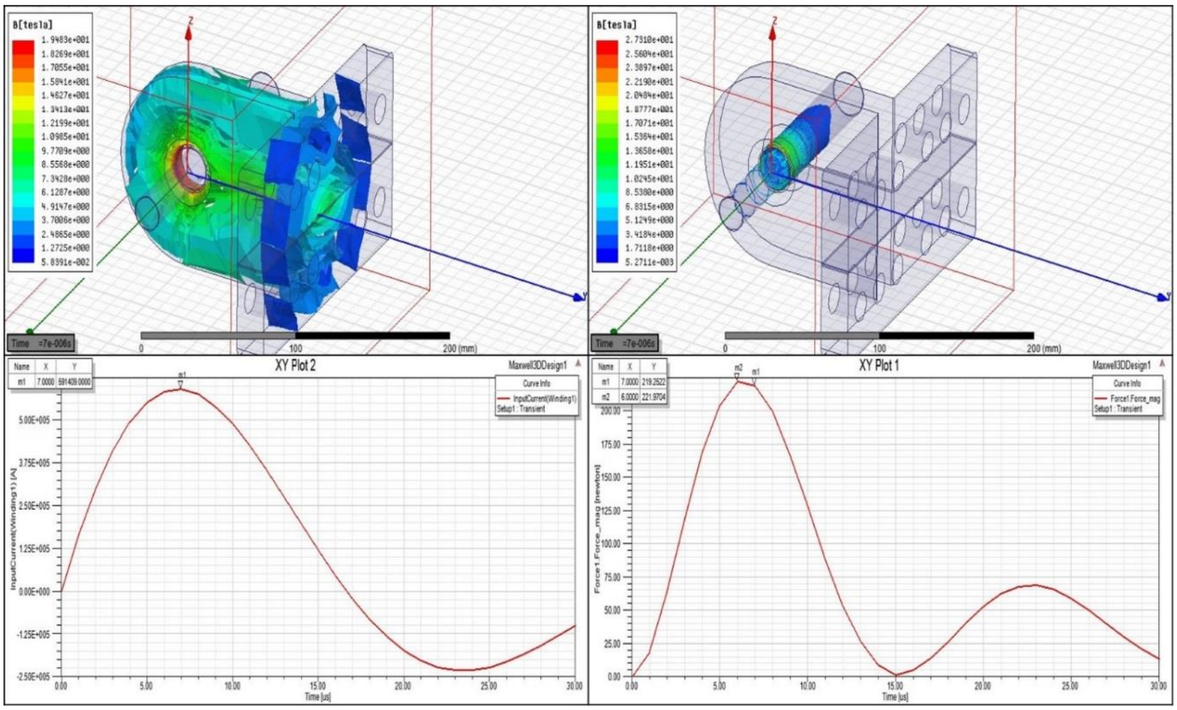

Fig 4.3 Cu Coil, AL – SS work pieces, 2mm Air-gap

4.2 Simulation of EMW of Cu-SS work pieces with Cu coil

The following simulation results (Fig. 4.4 to 4.6) are shown for electromagnetic welding of Cu-SS tubular work pieces with Cu coil at an air gap of 0.5, 1.0 and 2.0 mm respectively. At an air gap of 0.5mm, for the process parameters of 14KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 22.89T and 31.43T resp. and the maximum electromagnetic force generated is 280.68 N. Fig(4.4) shows the results.

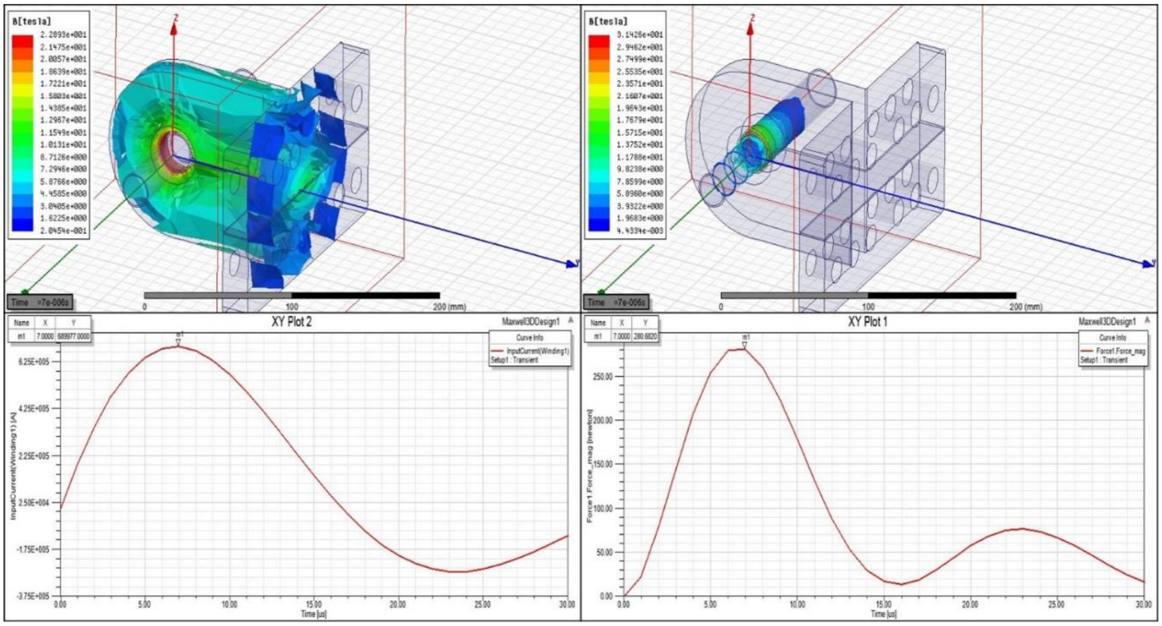

Fig 4.4 Cu Coil, Cu – SS work pieces, 0.5mm Air-gap

At an air gap of 1mm, for the process parameters of 14KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 23.21T and 44.69T resp. and the maximum electromagnetic force generated is 523.97N. Fig (4.5) shows the results.

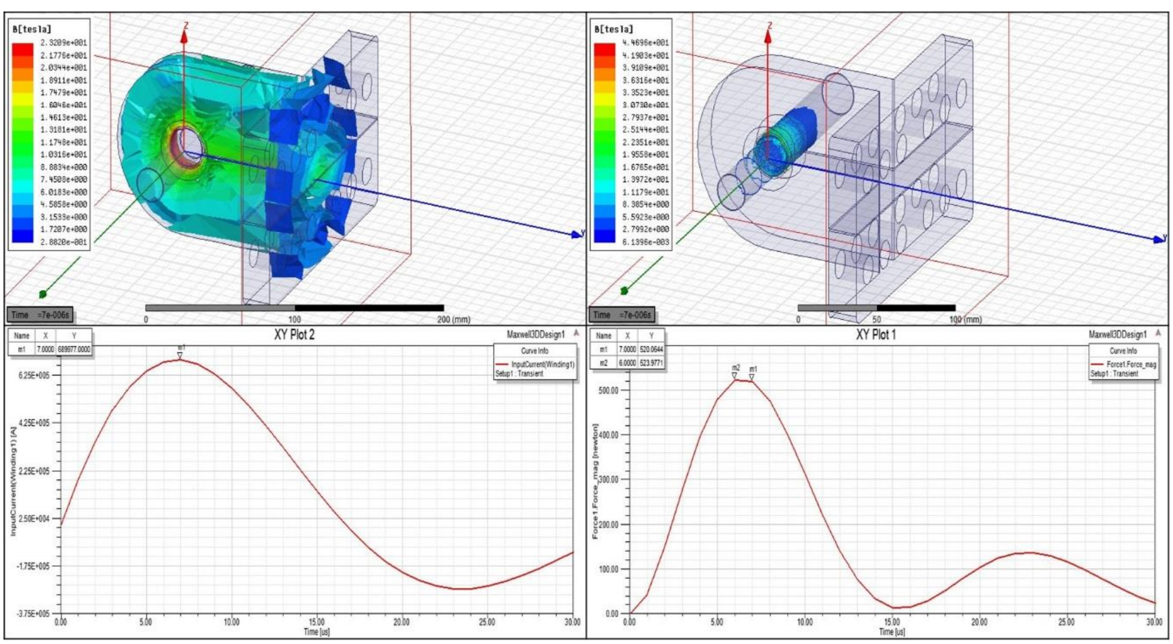

Fig 4.5 Cu Coil, Cu – SS work pieces, 1mm Air-gap

At an air gap of 2mm, for the process parameters of 14KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 22.95T and 34.45T resp. and the maximum electromagnetic force generated is 319.42N. Fig (4.6) shows the results.

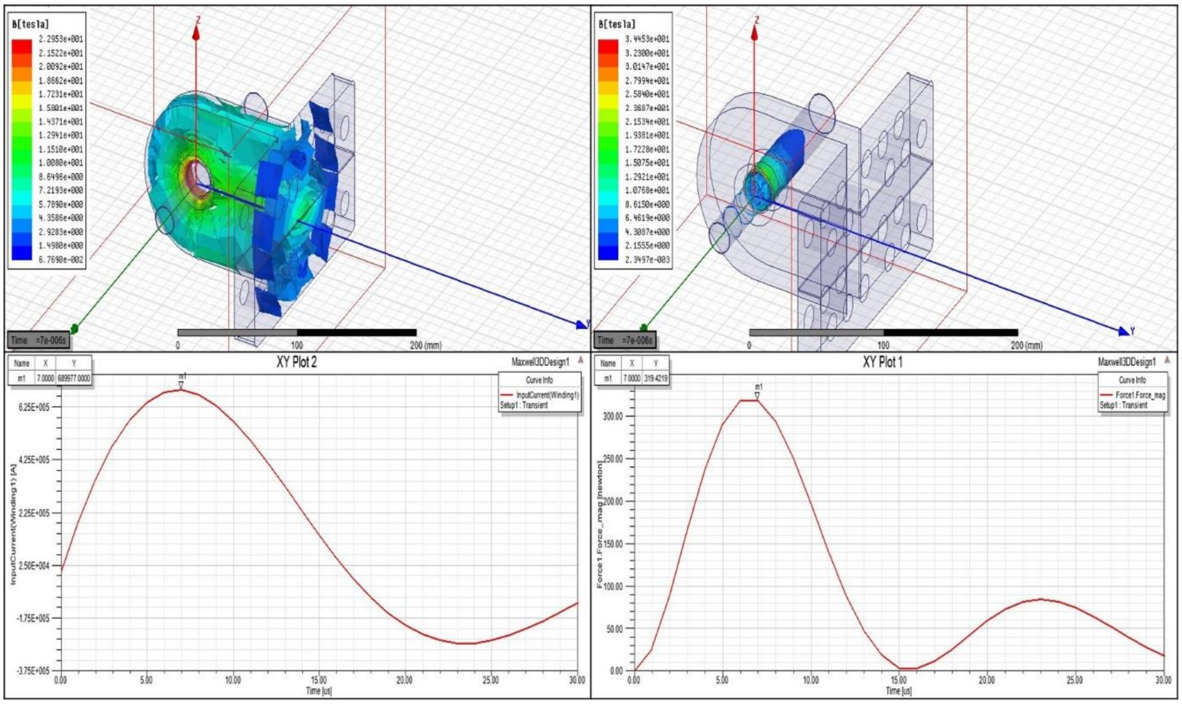

Figure 4.6 Cu Coil, Cu – SS work pieces, 2mm Air-gap

4.3 Simulation of EMW of SS-SS work pieces with Cu coil

The following simulation results (Fig. 4.7 to 4.9) are shown for electromagnetic welding of SS-SS tubular work pieces with Cu coil at an air gap of 0.5, 1.0 and 2.0 mm respectively. At an air gap of 0.5mm, for the process parameters of 18KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 25.66T and 25.33T resp. and the maximum electromagnetic force generated is 141.49N. Fig (4.7) shows the results.

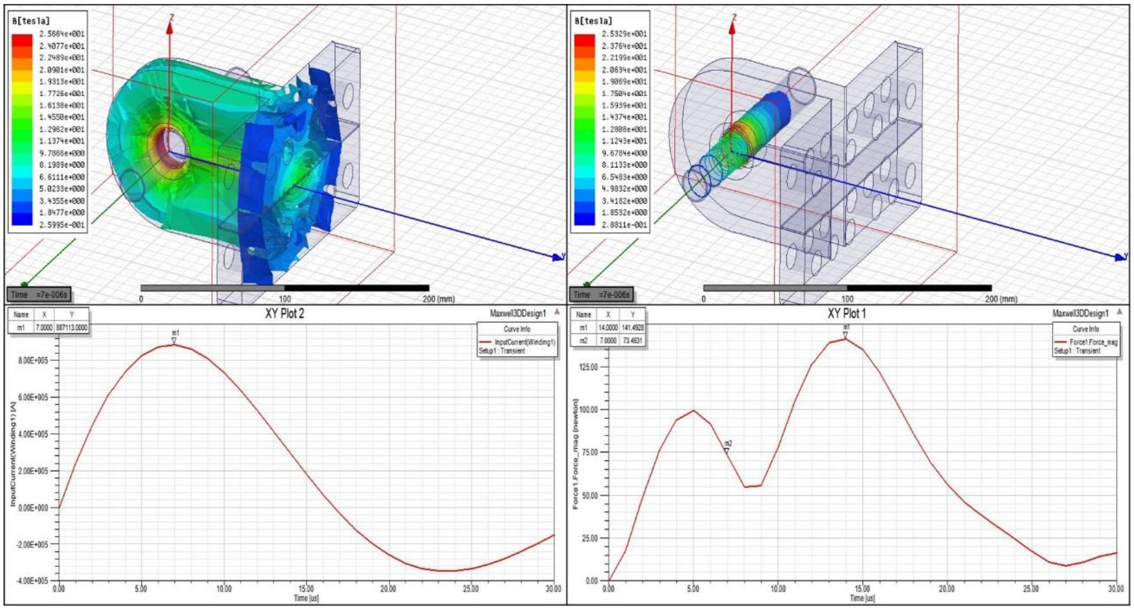

Fig 4.7 Cu Coil, SS – SS work pieces, 0.5mm Air-gap

At an air gap of 1mm, for the process parameters of 18KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 24.68T and 24.09T resp. and the maximum electromagnetic force generated is 416.192N. Fig (4.8) shows the results.

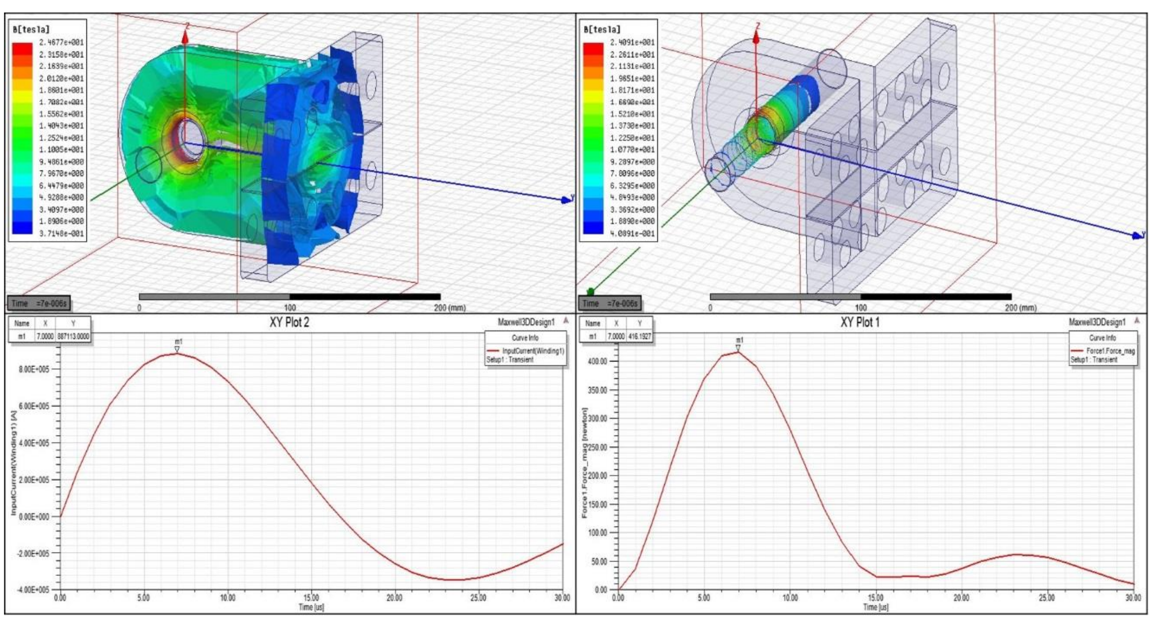

Fig 4.8 Cu Coil, SS – SS work pieces, 1mm Air-gap

At an air gap of 2mm, for the process parameters of 18KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 24.063T and 23.25T resp. and the maximum electromagnetic force generated is 105.80N. Fig (4.9) shows the results.

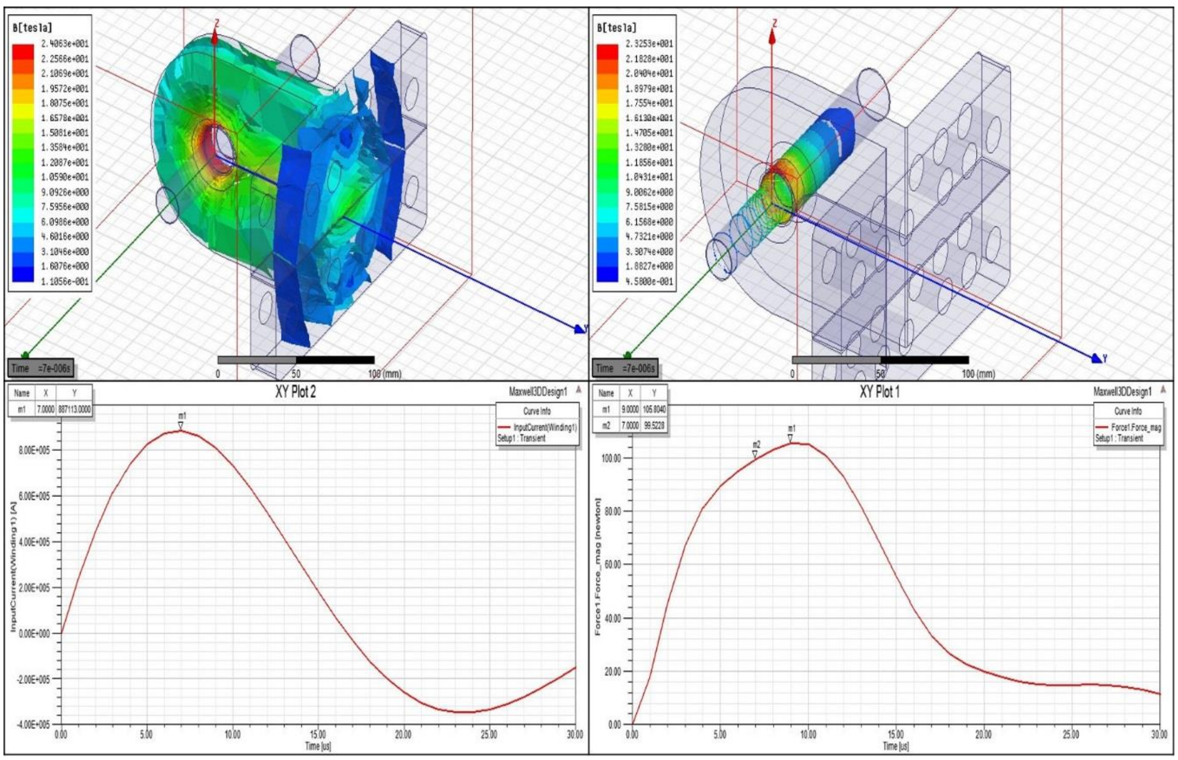

Fig 4.9 Cu Coil, SS – SS work pieces, 2 mm Air-gap

4.4 Simulation of EMW of Al-SS work pieces with SS coil

The following simulation results (Fig. 4.10 to 4.12) are shown for electromagnetic welding of Al-SS tubular work pieces with SS coil at an air gap of 0.5, 1.0 and 2.0 mm respectively. At an air gap of 0.5mm, for the process parameters of 12KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 19.58T and 26.25T resp. and the maximum electromagnetic force generated is 195.83N. Fig (4.10) shows the results.

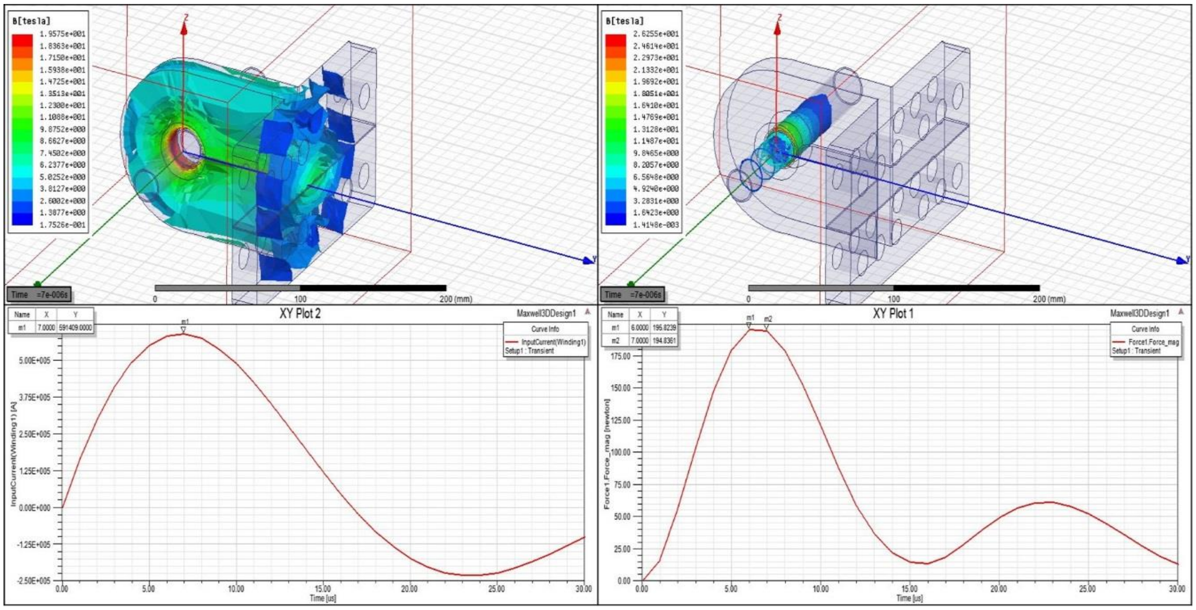

Fig 4.10 SS Coil, Al – SS work pieces, 0.5mm Air-gap

At an air gap of 1mm, for the process parameters of 12KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 19.82T and 34.23T resp. and the maximum electromagnetic force generated is 360.276N. Fig (4.11) shows the results.

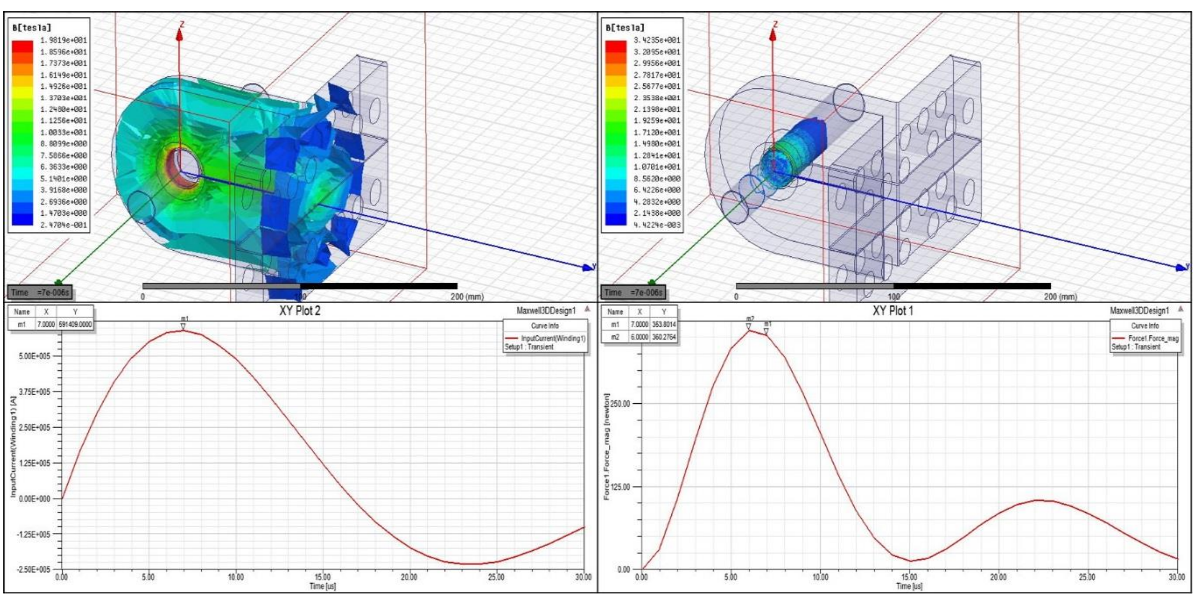

Fig 4.11 SS Coil, Al – SS work pieces, 1mm Air-gap

At an air gap of 2mm, for the process parameters of 12KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 19.48T and 27.31T resp. and the maximum electromagnetic force generated is 221.97N. Fig (4.12) shows the results.

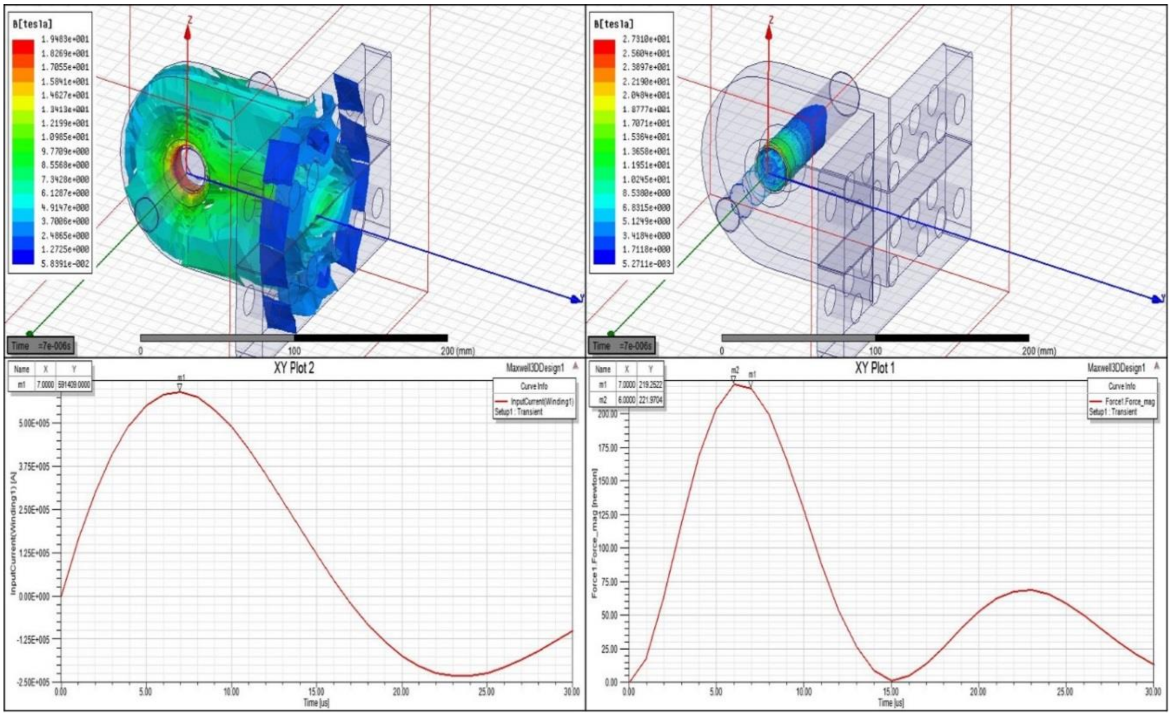

Fig 4.12 SS Coil, Al – SS work pieces, 2 mm Air-gap

4.5 Simulation of EMW of Cu-SS work pieces with SS coil

The following simulation results (Fig. 4.13 to 4.15) are shown for electromagnetic welding of Cu-SS tubular work pieces with SS coil at an air gap of 0.5, 1.0 and 2.0 mm respectively. At an air gap of 0.5mm, for the process parameters of 14KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 22.89T and 31.43T resp. and the maximum electromagnetic force generated is 280.68 N. Fig (4.13) shows the results.

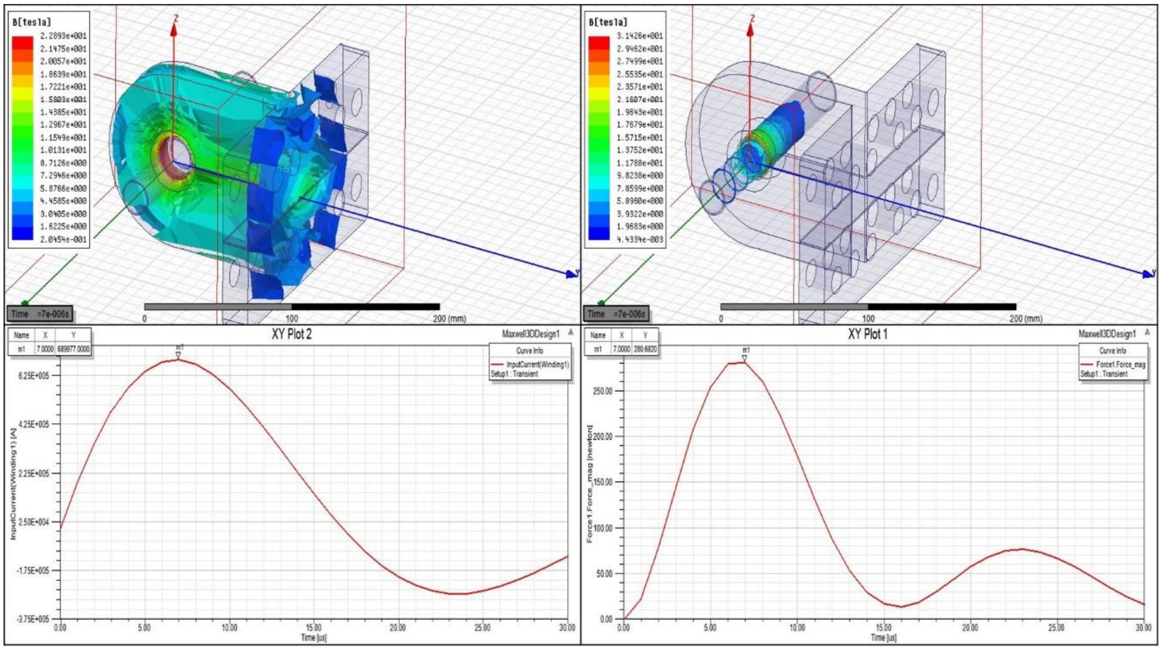

Fig 4.13 SS Coil, Cu – SS work pieces, 0.5mm Air-gap

At an air gap of 1mm, for the process parameters of 14KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 23.21T and 44.69T resp. and the maximum electromagnetic force generated is 523.97N. Fig (4.14) shows the results.

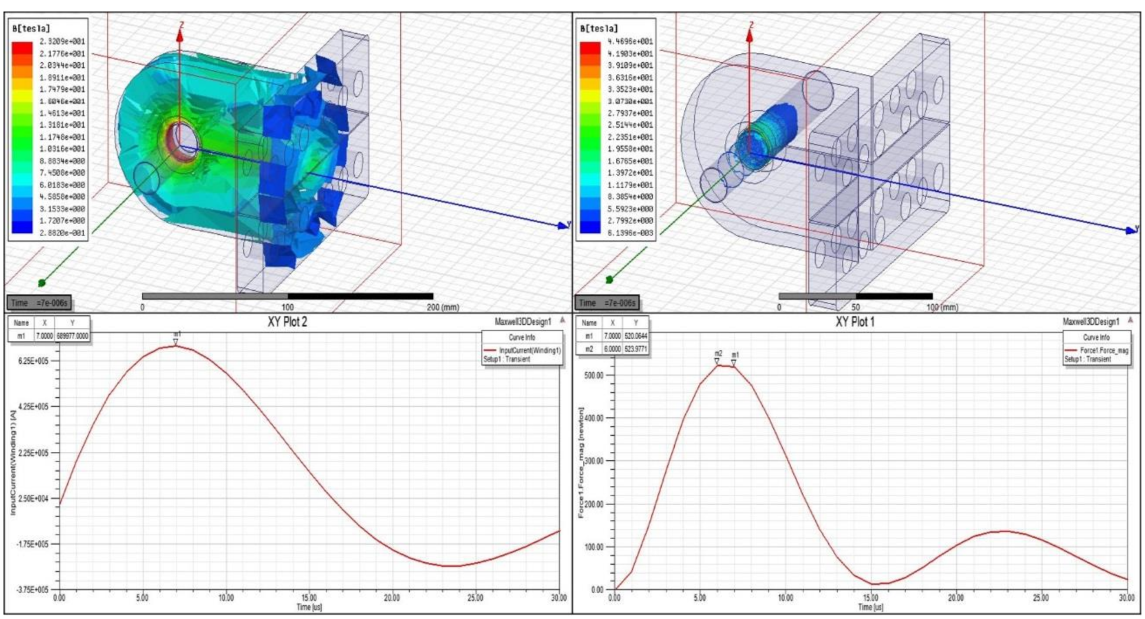

Fig 4.14 SS Coil, Cu – SS work pieces, 1mm Air-gap

At an air gap of 2mm, for the process parameters of 14KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 22.95T and 34.45T resp. and the maximum electromagnetic force generated is 319.42N. Fig (4.15) shows the results.

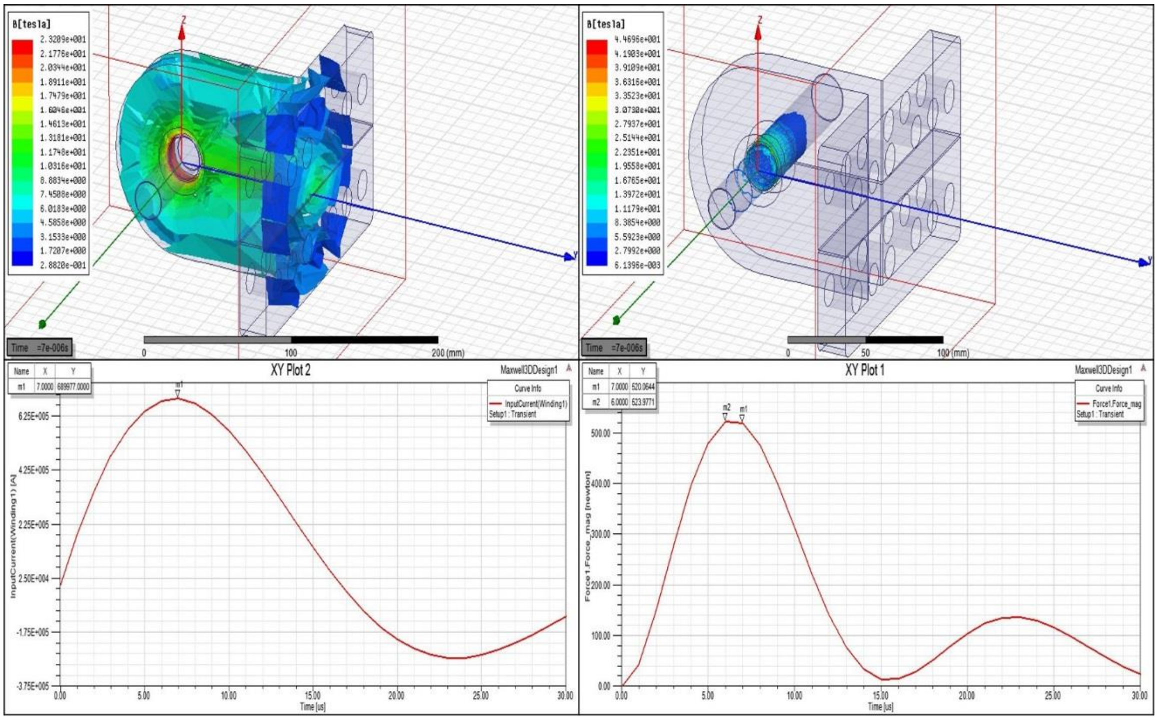

Fig 4.15 SS Coil, Cu – SS work pieces, 2mm Air-gap

4.6 Simulation of EMW of SS-SS work pieces with SS coil

The following simulation results (Fig. 4.16 to 4.18) are shown for electromagnetic welding of SS-SS tubular work pieces with SS coil at an air gap of 0.5, 1.0 and 2.0 mm respectively. At an air gap of 0.5mm, for the process parameters of 18KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 25.66T and 25.33T resp. and the maximum electromagnetic force generated is 141.49N. Fig (4.16) shows the results.

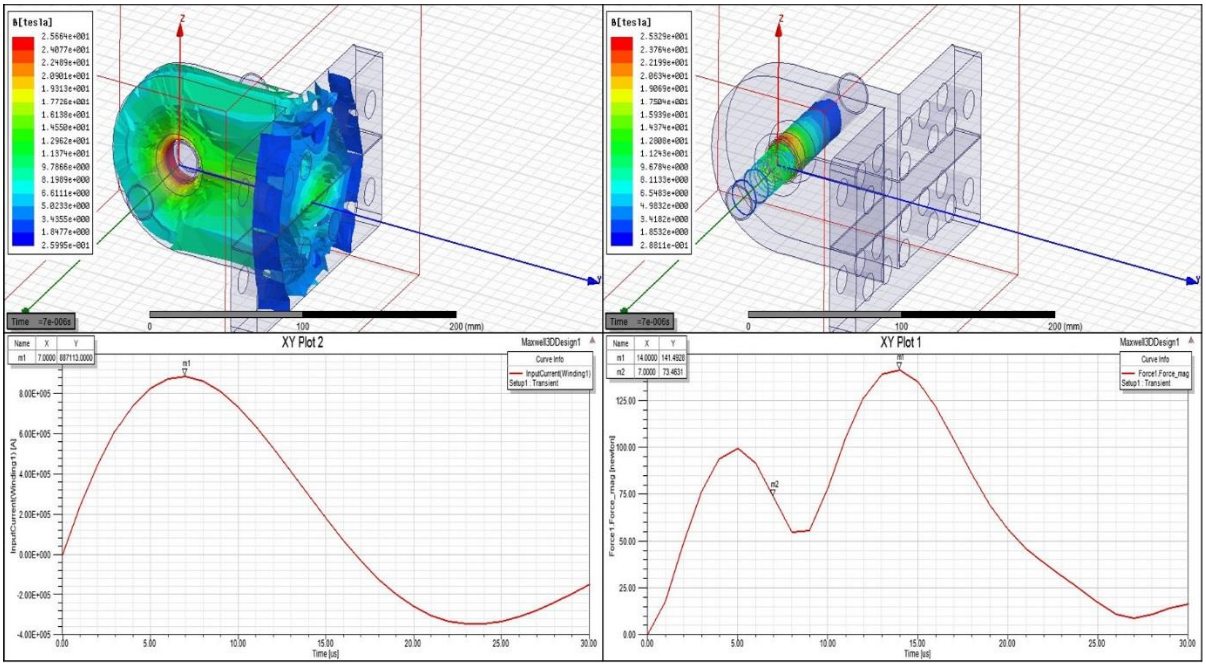

Fig 4.16 SS Coil, SS – SS work pieces, 0.5 mm Air-gap

At an air gap of 1mm, for the process parameters of 18KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 24.68T and 24.09T resp. and the maximum electromagnetic force generated is 416.192N. Fig (4.17) shows the results.

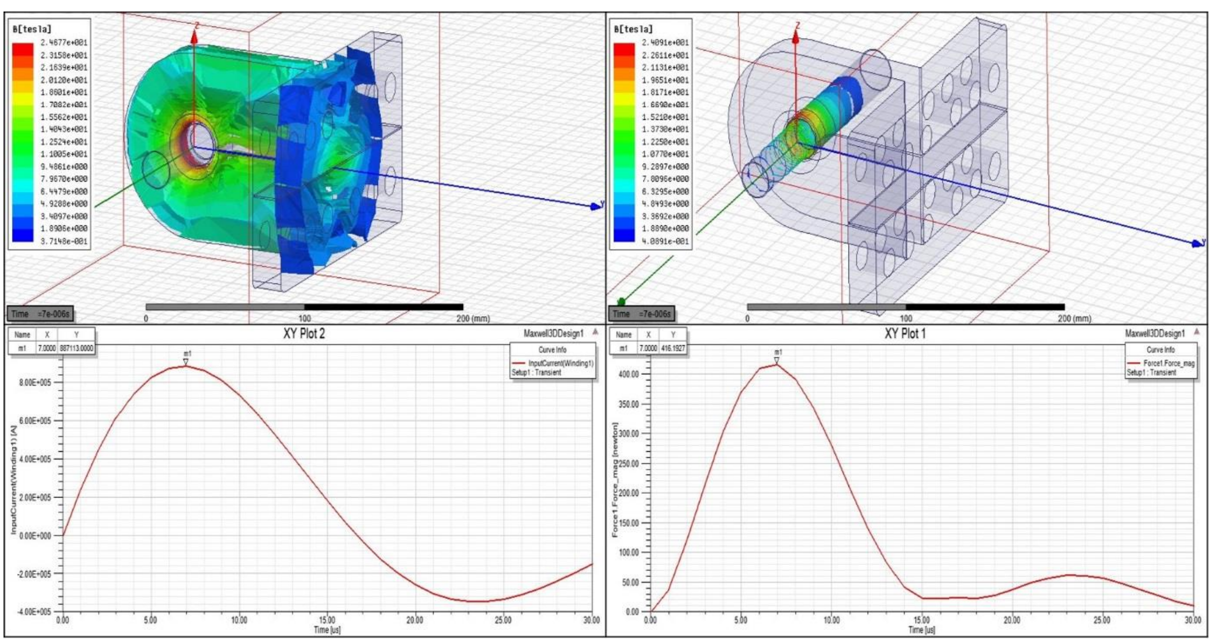

Fig 4.17 SS Coil, SS – SS work pieces, 1mm Air-gap

At an air gap of 2mm, for the process parameters of 18KV, 70 nH and 400 μF, the maximum magnetic field density generated for coil and work pieces is found out to be 24.063T and 23.25T resp. and the maximum electromagnetic force generated is 105.80N. Fig (4.18) shows the results.

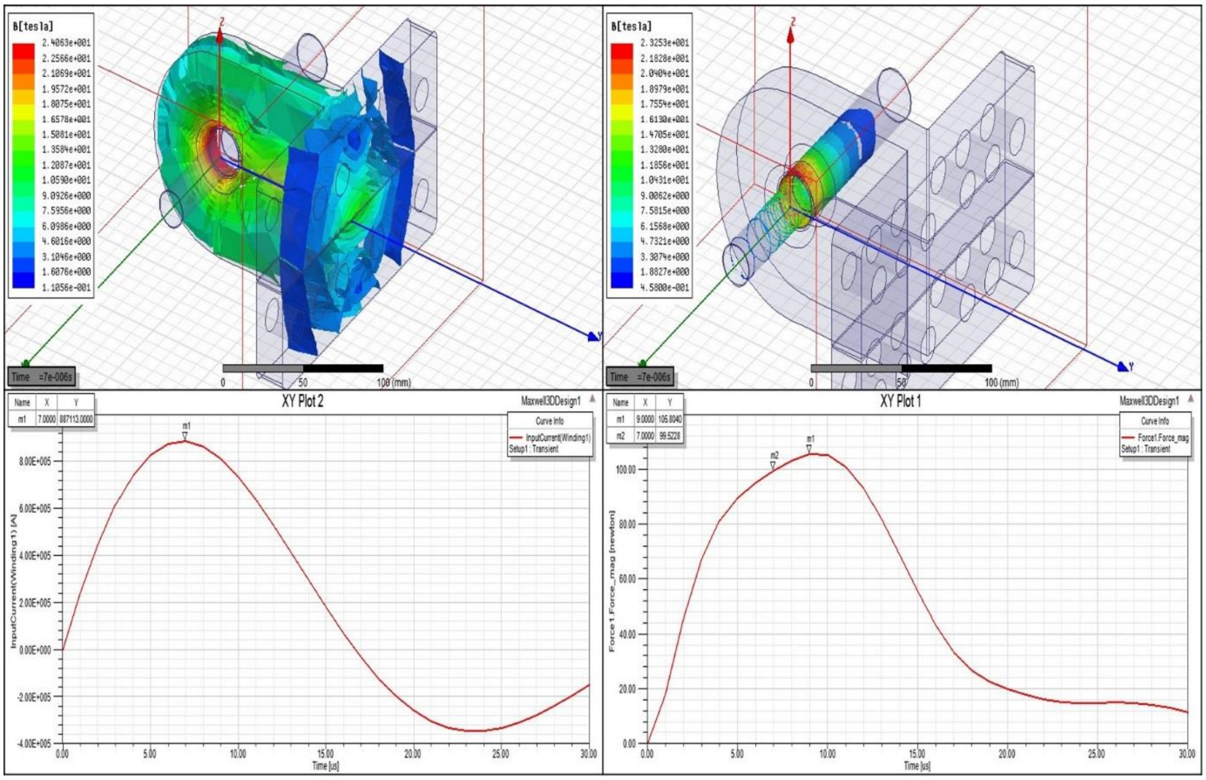

Fig 4.18 SS Coil, SS – SS work pieces, 2mm Air-gap

CHAPTER 5

5. Results and Conclusion

5.1 Results and Discussions

Welding simulations have been established between the similar metal combinations of Stainless Steel – Stainless Steel, and between dissimilar metal combinations of Aluminium – Stainless Steel, and Copper – Stainless Steel. Table 1. shows a detailed result of all the welding simulations carried out at different welding parameters.

The voltage was varied (from 12KV to 18KV) for different material combinations, because it's learnt from the literature, and verified from our results that, Copper being more dense than Stainless Steel, requires more energy to be welded. More density leads to less magnetic lines of flux passing through the material, which results in lesser Electromagnetic or Lorentz force. Also, energy required for Stainless steel is more as compared to Aluminium. Thus the energy requirement goes on decreasing successively for Stainless Steel, Copper and Aluminium.

In EMW process, the kinetic energy is partly utilized in welding process. The remaining kinetic energy is used to generate the impact velocity required for welding. Transient analysis were done on the model. The time varying current along with the geometry and mechanical properties were given as an input to ANSYS MAXWELL 3D software, which was used to calculate the Electromagnetic force and magnetic flux density.

The input energy goes on increasing with size of the job piece. The energy is the least for welding of aluminium and it successively increases for copper and SS. For welding of dissimilar combinations of these metals, the energy requirement is intermediate. When the input energy is applied, the EM force (Lorentz force) is generated in accordance with electrical conductivity of the job piece. Out of the total input energy, some part is spent in spark gap switch (in the form of light and sound). The remaining energy is distributed in the leads and the welding coil. Out of the energy, coupled to the coil, a part is coupled to job piece, depending on magnetic coupling between the former and the latter. The energy coupled to the job piece is initially spent in deformation of the job piece. Successively higher energy is spent for deformation for aluminium, copper and SS.

In this project, the air-gap has been varied between the outer and inner work piece, and the data corresponding to magnetic flux density and electromagnetic force required for welding have been evaluated. Fig (5.1) shows the graph of how air-gap varies with voltage for a particular combination of materials.

One can see from the results that, at first the Electromagnetic force is low corresponding to 0.5mm air-gap, but it increases, when the air-gap is increased to 1 mm. And then, it again decreases when the air-gap is varied to 2 mm. Thus, the Electromagnetic force and Magnetic flux density first increases, then decreases. One can conclude that this is because, at 0.5mm, the outer work piece doesn't attain enough velocity or force to impinge upon the inner work piece and get welded. Before it can reach its peak force, it strikes the inner tube. But at 2 mm, the outer work piece attains its maximum value of force, and then again decreases, as the distance, or air-gap is too large. Thus, one can conclude that, a stand-off distance of approx. 1mm is appropriate to weld tubular jobs by Electromagnetic welding process as it gives maximum electromagnetic force for welding. (Fig 5.2)

One can see from the result that the values of magnetic lines of flux for different sets of combinations of coil materials for Copper and Stainless steel, for a given value of air-gap, are the same. This is due to the fact that, the relative permeability of Copper is 0.999991 and that of Stainless steel is 1. Which would mean that copper gives a less resistance to the flow of the current compared to stainless steel. But Stainless steel (approx. 860 MPa) is mechanically much stronger than Copper (approx. 220 MPa). And since the relative permeability doesn't differ by much and since EMW is an impact welding process, the coil should be such that it'll resist the deformation during welding. Thus for the same values of voltage and air-gap, a stainless steel coil is preferred than a copper coil.

It is probable to establish scaling relationships for the input parameters for welding work pieces of different sizes and various materials. It is also possible to decide appropriate values of the capacitance and voltage for the capacitor bank, depending on the size of the job. The computational model developed needs to be validated with the experimental welding setup of the said material combinations. This analysis gives important inputs for the predictive design and the standardization procedures. This analysis is particularly important considering the scarcity of the data in open literature on this aspect.

Table 1: Results

Coil Material	**Outer Tube**	**Inner Tube**	**Outer Tube diameter (mm)**		**Air Gap (mm)**	**Inner Tube Diameter (mm)**		**Charging Voltage (KV)**	**Force (N)**
Copper	Stainless Steel	Stainless Steel	23	22	0.5	21	20	18	141.4920
			23	22	1	20	19	18	416.1927
			23	22	2	19	18	18	105.8040
Copper	Copper	Stainless Steel	23	22	0.5	21	20	14	280.6820
			23	22	1	20	19	14	523.9771
			23	22	2	19	18	14	319.4219
Copper	Aluminum	Stainless Steel	23	22	0.5	21	20	12	195.8249
			23	22	1	20	19	12	360.2764
			23	22	2	19	18	12	221.9704
Stainless Steel	Stainless Steel	Stainless Steel	23	22	0.5	21	20	18	141.4920
			23	22	1	20	19	18	416.1927
			23	22	2	19	18	18	105.8034
Stainless Steel	Copper	Stainless Steel	23	22	0.5	21	20	14	280.6820
			23	22	1	20	19	14	523.9771
			23	22	2	19	18	14	319.4220
Stainless Steel	Aluminum	Stainless Steel	23	22	0.5	21	20	12	195.8249
			23	22	1	20	19	12	360.2764
			23	22	2	19	18	12	221.9704

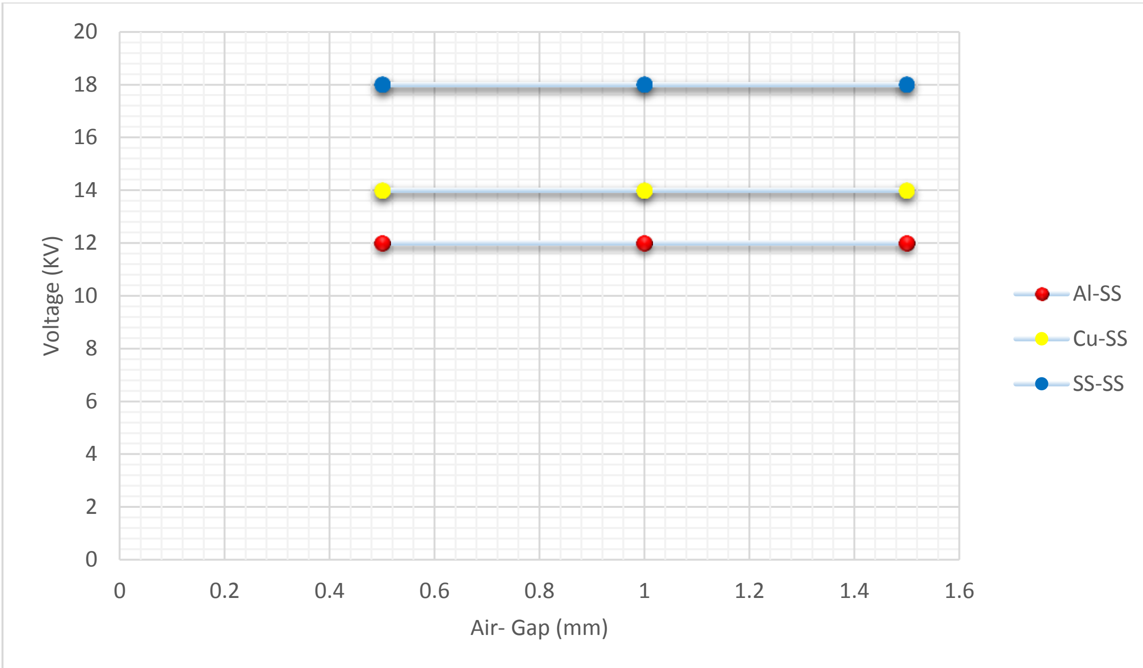

Fig 5.1 Air-gap (mm) v/s Voltage(KV)

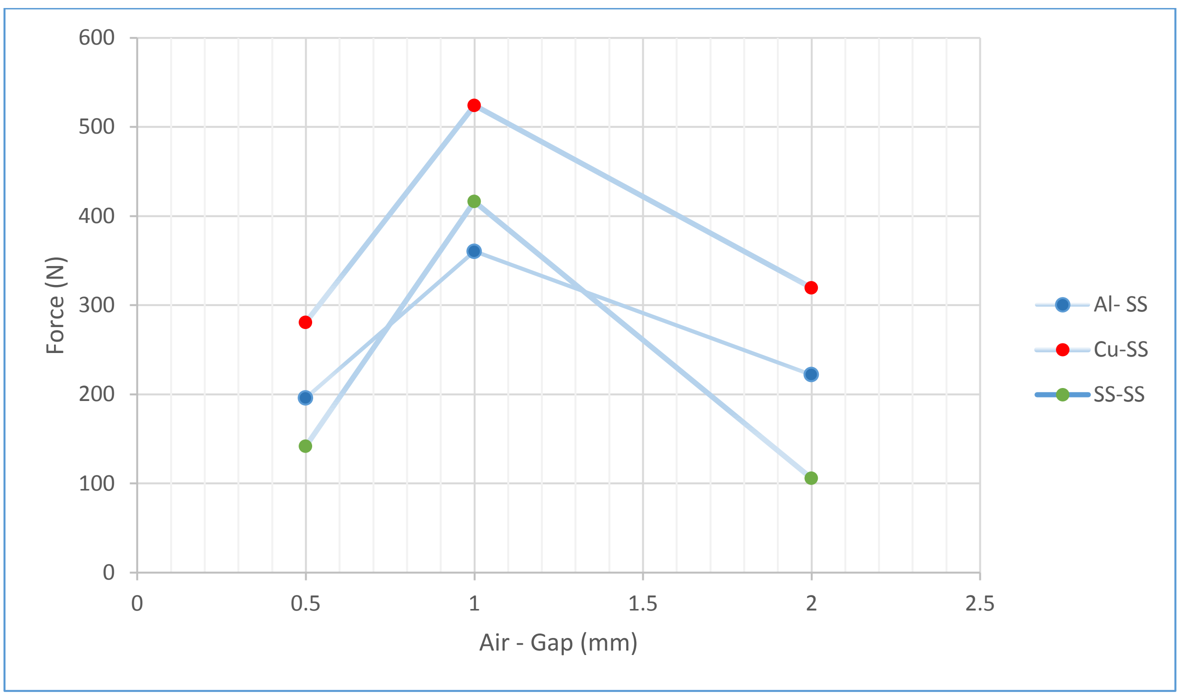

Fig 5.2 Air-gap (mm) v/s Force(N)

5.2 Conclusion

A comprehensive approach considering foregoing weldability criteria for magnetic pulse welding should be adopted. The process parameters in MPW are interrelated. A moderate input voltage at an optimum air gap could achieve a sound joint. The correctness of the computational model needs to be validated in actuality. This analysis gives important inputs for the predictive design and the standardization procedures. The publication of analytical results will provide highest possible information and can be utilized for further analysis and evaluation by future researchers.

5.3 Future Scope

Further research can be carried out for welding dissimilar material combinations of high refractory materials like niobium, titanium etc. Failure analysis of the coil could be performed to evaluate the life of the coil. Also, some research can be done in the field of utilizing this process for welding of tubular jobs of low electrically conductive materials, as electromagnetic welding of low electrically conductive materials is not explored for either plate to plate or tubular jobs.

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25. *SOUDIMMA : Electromagnetic pulse welding*